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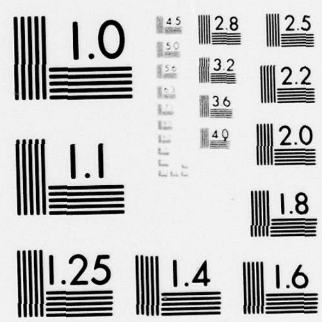

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ANALOGICAL REASONING AS A DISCOVERY LOGIC

by
Julian Weitzenfeld and Gary A. Klein

August 1979

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Prepared for the Air Force Office of Scientific Research.
Contract Number F49620-79-C-0179.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 TR-SCR-79-5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 ANALOGICAL REASONING AS A DISCOVERY LOGIC.		5. TYPE OF REPORT & PERIOD COVERED 9 Research Report,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Julian Weitzenfeld ~~and~~ Gary A. Klein		8. CONTRACT OR GRANT NUMBER(s) [redacted] F49620-79-C-0179 15
9. PERFORMING ORGANIZATION NAME AND ADDRESS Klein Associates 740 Wright St. Yellow Springs, Ohio 45387 394 586		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 2313/A2 17 A2
11. CONTROLLING OFFICE NAME AND ADDRESS United States Air Force Air Force Office of Scientific Research Bolling AFB, D.C. 20332		11 ~~12. REPORT DATE~~ ~~August~~ Aug, 1979
		~~13. NUMBER OF PAGES~~ 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 26 p. 61102F		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Analogical inference
Reasoning by analogy
Inferential processes
Scientific discovery

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(See Abstract)

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Abstract

Reasoning by analogy is an important means of generating hypotheses about new situations. Psychological research on analogical reasoning has been limited to the format of mathematical proportions. However, this treatment of analogical reasoning is not consistent with the aspect of analogical reasoning that generates hypotheses. A more viable approach is taken by philosophers of science such as Hesse (1966), whose work is used to provide a description of a psychological process of discovery. The key elements of this description include (1) selecting the analogue; (2) comparison of analogues to establish points of correspondance; (3) classification of correspondances into similarities, dissimilarities and neutral features, and (4) refining causal descriptions.

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Analogical Reasoning as a Discovery Logic

One important aspect of analogical reasoning is that it is a discovery logic, a means by which hypotheses are generated, rather than tested. Our intention is to examine this aspect of analogical reasoning. We suggest that the hypothesis-generating quality of analogical reasoning is an important and overlooked area for psychological research. It has been overlooked in large part because of the reliance of psychological research on analogy on the mathematical proportion paradigm. However, research modeled on mathematical proportions will not identify the properties of analogical reasoning that generate new hypotheses. Philosophers of science have paid more attention to the use of analogy for hypothesis generation.

This paper will examine a philosophical analysis of analogical reasoning and then present the psychological processes it suggests. This framework will then be used to evaluate psychological research on analogical reasoning.

A Logic of Discovery

Peirce (1934-35) proposed that there are three types of reasoning: deductive, inductive, and abductive. Deduction draws the consequences of hypotheses; induction concerns the support a hypothesis gets from evidence; but abduction is reasoning that suggests the hypothesis in the first place. It has been controversial among philosophers whether there is a logic of abduction. Some have claimed that the origin of hypotheses is merely psychological, but Peirce and, more recently, Hanson (1958), Harré (1970), and Hesse (1966) have argued

that there are reasons for proposing hypotheses quite aside from the later reasons for accepting or rejecting them. These reasons are the domain of a logic of abduction.

The nature of abductive arguments is such that they cannot be conclusive arguments, nor do they necessarily lead from a given set of premises to a unique conclusion, but they are the only type of inference that can yield new ideas. Harré and Hesse have given accounts of abduction as analogical reasoning.

In the psychological literature, abduction has commonly been confounded with induction, as in studies of concept learning and of the induction of a rule from a series. We shall follow Peirce in distinguishing induction from abduction. Induction involves judgments of the evidentiary value of tests and instances, and is often modeled (with little verisimilitude) by the probability calculus (see Cohen, 1977; Kahneman and Tversky, 1973). Induction is quite distinct from the reasoning that generates hypotheses-- abduction. Both kinds of reasoning, as well as deduction, are necessary for the solution of most problems.

Analysis of Analogical Reasoning

The psychological study of analogical reasoning should begin with a fairly full description of examples of such reasoning, just as any scientific investigation should begin with a close examination of a phenomenon in its naturally occurring form. Then an account would be generated of the separate activities involved. Hesse's (1966) account of how new phenomena are understood by analogy to already known phenomena (material analogy) provides an initial description and some analysis. We intend to give here a more complete account of the

psychological activities involved in reasoning by material analogy.

We do not propose either a computational model or a componential model of analogical reasoning. If our general description is correct there are difficulties, probably insuperable ones, in creating any such model complete enough to predict human behavior with any precision. These difficulties derive from the extent and variety of information called upon in analogical reasoning. On this basis we shall provide a critique of the dominant experimental paradigm for reasoning by analogy and of the models based upon it. Our account, on the other hand, can suggest methods of improving problem solving behavior, does have testable consequences, and has the advantage of coming closer to a description of naturalistic behavior.

Hesse distinguishes among several types of analogies: formal analogy, conceptual analogy, analogue models, and material analogy. The first of these is based upon the model of a scientific theory as a formal calculus, a system like mathematics or mathematical logic in which terms are explicitly defined and in which new statements are derived from old ones by the application of explicit rules of inference. Such a calculus only becomes an empirical theory when the terms of the calculus are given an interpretation in real world variables. A good example of a calculus having more than one interpretation is the standard wave equations. One interpretation of the calculus assigns to the terms in the equations measurable features of sound, such as pitch and volume. Another interpretation assigns features of electromagnetic phenomena. Yet another applies to jump ropes. A formal analogy in Hesse's terms exists between two interpretations of the same calculus, as between sound waves and electromagnetic waves. These quite different phenomena are described by the same equations. A conceptual analogy

is a wholly imaginary mental construct used as an interpretation of such equations, such as the electron cloud interpretation of quantum equations. Analogue models are the familiar models such as airplane mock-ups, in which copies of an object are made that differ from the target in scale.

New hypotheses in science, however, are generated by material analogies--comparisons between two items that actually exist (and are not merely mental constructions), such as objects or events. A formal theory, such as a mathematical model in psychology, is a representation of established relationships among terms already known to be empirically significant. Although new predictions can be made from it by deduction, and such predictions follow with logical necessity from the theory, they are limited to new relations among the properties already described. They cannot suggest new properties to investigate. On the other hand, material analogy, although less certain because it depends upon the loose relations of similarity, can suggest new properties to investigate. It is this feature in which Hesse is interested. She is concerned to show the logical basis for such reasoning, why analogies can provide good reasons for considering a hypothesis. In doing so, however, she provides material for an account of the psychological processes for analogical reasoning. We shall derive a psychological description from her account of the logic.

Hesse's Account

Hesse says that the input of analogical reasoning consists of two important bodies of information. The first is the set of similarities between some observed properties of the new domain and

those of an old domain (the analogue selected). The second is the known set of causal relationships in the old domain. Analogical reasoning to new hypotheses is an extrapolation from the known causal relations in the old domain to similar relations in the new domain. The justification for such proposals, which are merely suggestive arguments and never conclusive, is the set of observed similarities between the two domains. So, for example, if one understands mammalian feeding behavior as a sophisticated form of the feeding/satiety reflexes in the blowfly, the similarities between rats and blowflies is the basis of the analogy, and those similarities also determine what hypotheses will be suggested about the causal relationships in the rats. The research will be rich in hypotheses about interactions between excitatory and inhibitory neural controls, the known causal relations in the analogue. But the work will be poor in hypotheses about interactions with mammalian digestion (Davis & Levine, 1977).

On Hesse's account, then, reasoning by material analogy requires:

1) Selecting a material analogue. Hesse's description does not explain the purely psychological process of selecting an analogue. We see this as a recognition of similarity that is related to recall and to perceptual learning. It is a form of identification as similar to. The criteria of sufficient similarity, which are relative to a task in all cases (including learning and recall experiments), are here more loose. The degree of similarity required for the analogue to be recalled depends upon ecological considerations. In everyday problem solving situations we expect to find changes through the problem solving process in the amount, and indeed in the kind, of similarity required for an item to be recalled as an analogue; loose analogues may prove insufficient or tight analogues may be hard to find.[1]

Our account of the retrieval of an analogue is related to the work of Norman and Bobrow (1979) on memory retrieval. They postulate a theoretical entity, the <u>description</u>. In a computational model of retrieval the description is a "collection of perspectives" that is derived from the recall context and is used to guide the recall process. Among its features is that it permits the amount of specificity needed for retrieval of an item to vary according to the situation. Our account, however, is of the use of memory in problem solving and not the retrieval of a specific item from memory.

Selection of an analogue, however, is even more context-relative than Norman and Bobrow's account of memory retrieval. For Norman and Bobrow, the retrieved item will either be correct or incorrect. But analogues are not evaluated as correct or incorrect at all. They vary in degree of aptness for the problem at hand. Two analogues can be equally apt, but in different ways. Not only the specifications for the retrieval process, but also the subsequent evaluation are context dependent. Analogue retrieval is in this way different from the standard categorization paradigm. Therefore, models of categorization, such as templates or feature extraction, will not be adequate for an account of analogical reasoning. A two-valued evaluation, such as "correct vs. incorrect" or "category member vs. non-member" requires a pre-existing category or standard with which the retrieved product is to be compared. "Identification as similar" is a more flexible, generative process that can only be evaluated by ecological, or contextual, considerations. It is a way of creating categories rather than a result of category matching.

2) <u>Establishing correspondances between the causal relationships in the analogue and the target domain</u>. This generates hypotheses

about causal relationships among the properties of the target domain. For example, the excitatory and inhibitory neural reflexes of the blowfly are seen to correspond to the hypothalamus of the rat, generating hypotheses about the rat hypothalamus and feeding behavior.[2] This is also a recognition of similarity, this time acting on aspects of the analogues. The identification as similar process need not be a different psychological process for selecting an analogue and for establishing correspondances to the target domain. It just must be flexible to act on inputs of quite different ontological types, including events, objects, and properties, and must be sensitive to context. Because it must be this general to do the initial retrieval job, it is sufficient for establishing the correspondances also.

3) Classification of correspondances into similarities, dissimilarities, and neutral features. In any analogy there are both similarities and differences between the two domains (the target domain that needs to be better understood and the analogue selected to provide illumination). In the example above the similarities include neural control over feeding, which has been demonstrated in both blowflies and rats. The dissimilarities include biological features of the digestive systems of the two organisms. The existence of dissimilarities does not invalidate the analogy. There will always be some dissimilarities between two domains, otherwise they would be identical or one would be a subclass of the other. (However, the extent and nature of the dissimilarities may make a candidate domain appear to be less likely to serve as a source of new discoveries.)

Besides the known similarities and dissimilarities between the domains there are also neutral features, properties for which similarity or dissimilarity has not yet been established. An important

part of the process of scientific theorizing is moving properties from the neutral status to one of the known categories. Hesse claims that these neutral features create the possibilities for new hypotheses. Neutral features are what is missing from formal analogies.

Distension of the blowfly foregut generates the inhibitory feeding reflex. This was a neutral feature when researchers did not know whether similar mechanisms were at work in rats. What in the rat corresponded to distension of the blowfly foregut? Research did not reveal any comparable local mechanism, but instead has shown the importance of an interaction of local, central and peripheral cues. Thus, attempts to explore the neutral analogy have stimulated a greater understanding of mammalian motivated behavior and moved neutral features, e.g., features whose analogical status was unknown, clearly into the class of negative analogies. This, in turn, calls for a search for a new dominant analogue to suggest models for the interaction of information from various sources.

4) Refining the causal descriptions. The understanding of each domain, the analogue as well as the target, must constitute a plausible causal model. This assumes that we are able to recognize and repair flaws in a causal model, that we have at least psychologically, if not logically, a conception of what counts as a good causal description. This is the kind of factor that tends to be omitted from psychological research because it has historical and cultural roots. Most of our criteria for a good causal model are learned and have developed within Western culture.[3] It is difficult to create good experimental models of how they are used in a new context. Nonetheless, they are an essential part of reasoning by analogy (even of the impoverished examples in the proportion format, to be discussed below).

An example of refining the causal story would be if there were no apparent neural connections between the hypothalamus and the stomach. We would want to know how the hypothalamus normally is informed about nutritional needs. There would be a search for some link between nutritional status and hypothalamic activity to fill out the causal description. We have other criteria for defects in a causal description. Even if a model is a complete, or sufficient, causal chain, questions would be raised about its causal efficacy if it were to be found not necessary to bring about the result, e.g., if some other mechanism could also bring it about. For example, if a lesion in the path did not produce a decrement in performance, questions would be raised about the causal role of the neural path.

Here is a more homely example, exhibiting the interplay between our understanding of target and analogue: A new acquaintance is identified as being like Jack's uncle. Jack has had many arguments with his uncle and on the basis of this analogy it can be predicted that Jack will have many arguments with this man. But if they don't have such arguments and this leads Jack to recognize that his uncle was domineering whereas his new acquaintance is not, he can draw the hypothesis that it is the domineering aspects of his uncle that cause the arguments. These domineering aspects are part of the dissimilarities between the domains and so he no longer infers analogous causal effects about his acquaintance. (This method resembles John Stuart Mill's methods of agreement and difference for establishing causal sequences.)

The comparison of the analogue to the new situation allowed us to identify a causal relationship (when Jack interacts with domineering people he winds up having arguments with them) which clarifies relationships in the analogue, but which highlights a point of

dissimilarity between the analogue and the current situation. It is important to notice that the discovery process not only reaches forward, to use past experience to understand new encounters, but also reaches backward to allow the reinterpretation of past experience in light of new observations.[4] Each description must be a coherent causal account and a method of filling in causal lacunae in either story can suggest alterations in the other story.

The role of assimilated cultural standards such as causal coherence and adequacy are important in determing how the analogues are used. This is what we meant above by the variety of learned information acting on the process. Not only is a previously learned analogue retrieved, but the criteria of relevance are also given before the problem is set. We consider it a major defect in current computational and componential models of problem solving and of analogical reasoning that they attempt to model human thought as if it were culture free. There is another tradition that considers the social origins of higher mental processes and provides experimental evidence for this (e.g., Luria, 1976; Cole and Scribner, 1974). It is ironic that even as cognitive scientists begin to represent cultural context in computer programs, such content is absent from putatively psychological models.[5] We shall show below how culturally generated information is required for all analogical reasoning, even abstract psychometric examples. Our point here, however, is that some conception of causal adequacy is necessary for reasoning by analogy.[6]

The psychological processes called for by analogical reasoning as described above include: 1) selecting the analogue, 2) comparison of analogues to establish points of correspondance, 3) classification

of correspondances into similarities, dissimilarities, and neutral features, 4) refining the causal descriptions. Together in various sequences these processes may explain how people use concrete experiences to explore new situations. Since analogical reasoning does not have the logical force of deduction it may yield false, or misleading, conclusions. False expectations, which appear as errors in deductive models of thinking, may be explained by a model of analogical reasoning.

Research on analogical reasoning: The proportion format

Psychologists have neglected material analogy; they have preferred the more easily controlled analogies among concepts or among abstract representations such as Raven's matrices (Raven, 1938). The prototypical format has been that of the mathematical proportion: A is to B as C is to ____. We believe that concentration on this format may have resulted in psychologists studying as deductive inference many problems that subjects actually approach with material analogy strategies. For example, the findings of Kahneman and Tversky (1973; Tversky and Kahneman, 1974) on inductive reasoning produced exactly the kinds of deviation from a deductive "rational optimum" that might be expected from an analogical process, e.g., overvaluation of representative, available, and imaginable instances and undervaluation of sample size.[7]

Hesse discusses the limitations of proportionality as a model of analogical reasoning. All terms in a mathematical proportion are uniquely determined, e.g., 2:4::32:64. This is not true of an analogical relationship, e.g., Fish:fishtail::bird: tail or leg, and is part of its potential for generating hypotheses. Moreover,analogical reasoning does not share some of the formal properties of mathematical proportions.

For example, they are not transitive. Scout:army::whiskers:cat and whiskers:cat::mustache:man, but it does not follow that scout:army:: mustache:man.

There are additional limitations of the proportion model of analogies. It excludes most of the activities described in the previous section as playing a role in the generation of hypotheses. Subjects do not have to select an analogue, since they are already given both the term for the target and for the analogue domains.

These are serious limitations. We can examine them in greater detail by seeing how peculiar it looks if we try to fit material analogy to the proportion model. We shall call the respective terms A, B, C and D as in A:B::C:D. A single analogy would become a series of problems in which the C term, the target domain, is presented and the problem solver must find first an appropriate A term, the analogue, then a series of appropriate B terms. In the example of feeding behavior, the C term is rat feeding. First the feeding of a blowfly is selected as an A term. Some part of blowfly feeding, e.g., central neural control, is selected as the B term in the proportion. Only now is the problem filled in as completely as in the standard psychometric format. The remaining question is: <u>Blowfly feeding is to blowfly neural control as rat feeding is to ---------</u>. The answer "hypothalamus" is found. (We have not considered the further deviations from ecological validity produced by the multiple choice format for selecting the D term.) The process is presumably iterated to more and more precise elements of blowfly neural activity, generating more and more precise hypotheses about rat hypothalamus activity and feeding control.

The inadequacies of this description are manifest. Under

natural circumstances a person is interested in an analogue as part of some problem solving activity. There is some goal, some solution state, serving as criterion for the adequacy of the analogy, or for what counts as a correct answer. More than one analogy may be selected; an analogue may be rejected without its being "incorrect." Adequacy in goal-oriented tasks is not a two valued decision: correct or incorrect. But this ecological criterion of analogue suitability is replaced in the psychometric situation by the selection of a correct answer by the test makers or experimenters. What counts as a correct answer will depend upon what the testers consider relevant similarities among the items. If a subject should notice systematic differences in the density of ink in a question, that does not count as a relevant similarity. In the psychometric situation the domain of relevant similarities is essentially culturally defined. That is, items are tested against a population and to solve the problem posed means to discover the similarities accepted as relevant by the standardization sample. Here is the implicit reference to culturally acquired criteria. They determine the relevant similarities. There is no explicit list of relevant similarities in psychometric studies. This is the same appeal to our implicit knowledge of our culture that we appealed to in failing to list criteria for a causal account. In the psychometric situation this accounts for the charge of cultural bias in the use of analogy questions.

However natural or obvious a particular answer may appear, these answers are not logically valid in the way mathematical proportions are. What counts as a correct answer depends on the experimenter's or the culture's criterion. It is an open question what distortions are

introduced into the reasoning process by asking subjects to match the experimenter's, or the culture's, criterion, instead of working within the framework of a personally, logically, contextually, or ecologically defined goal. That is, any model based upon answers to multiple choice proportion format questions may not apply to analogical reasoning in more open situations.

The cognitive models of analogical reasoning have been tied to the proportion format used in research. Sternberg (1977a,b), in reviewing the available models, identifies as component processes of analogical reasoning the processes of encoding, inference, mapping, application, justification (an optional process), and preparation-response. Encoding is the translation of a stimulus into an internal representation. Inference is the process that discovers the rule relating the two terms of one analogue, e.g., A and B, or C and D. Mapping is the process discovering the higher order relation between the first terms of each analogue, e.g., A and C. Application is a process that generates and evaluates candidates for the fourth, or D, term of the analogy. Justification applies in forced choice analogies in which the generated answer is not part of the given answer set. It selects the best of the options offered. Preparation-response essentially includes everything else.

Sternberg (1977a) notes that the various models employing some or all of these components specify neither the domain of relevant attributes nor how the subject discovers this domain. Pellegrino and Lyon (in press) note that Sternberg's own results indicate that "encoding and preparation-response processes are more important in accounting for item difficulty and individual differences" than the

other features, but that these key processes are ones not modeled in Sternberg's account. Without committing ourselves to the adequacy of these accounts for solving analogies in the mathematical proportion format we would like to note several further difficulties introduced when the existing accounts are applied to reasoning by material analogy.

The target phenomenon, the C term, is given, but because the A term (the analogue) in the proportion format is retrieved from long-term memory it already is in an internal representation and need not be encoded. Instead of the encoding process there must be a retrieval process cued by the C term of the analogy. The target term itself, however, is not sufficient to select an analogue (A term) because the problem would just be "Find something similar to C," and, of course, there are infinitely many such similarities. The retrieval must be guided by a further sense of what the relevant similarities must be -- the needs of the reasoner and his purpose in seeking the analogue. This presupposes that information about the relationship between analogues is available <u>prior</u> to the retrieval of the A term.

Reasoning by material analogy cannot be described by current model then, because: 1) They have no retrieval component; 2) Retrieval must be guided by criteria of aptness of the analogue for the problem at hand, and so mapping of the A and C terms begins with a dominant similarity already available. This dominant similarity guides the further mapping processes. Retrieval and mapping are not independent processes as in current componential models; 3) Similarly, inference of B and D terms is not independent of other processes. It will be guided by the same contextual needs that guide retrieval and mapping.

Moreover, it would have to be guided by a model of causal adequacy; 4) Refining the causal descriptions replaces the other processes in current componential models. The process is more complex than the mere application of an inferred rule. It also requires a model of causal adequacy. The output cannot be evaluated as right or wrong, but requires some relational ("more apt than," or "sufficiently apt for") evaluation.

We suspect that the processes active in material analogy are not disconnected when solving psychometric puzzles. Because of their problem-specificity the models of proportion-format analogical reasoning are unlikely to be accurate. A similar argument is presented by Pellegrino and Lyon (in press), who demonstrate that the coding process is unlikely to be "context independent." They give an example of how context is likely to influence encoding: the difference between wane:wax and polish:wax.

If analogy problems in the proportion format are as closely related to general problem solving ability as many investigators think they are, the relation remains to be described. It seems clear that the component operations, their purported independence, their sequence and their acultural nature as proposed for proportion format problems cannot account for reasoning from material analogy. It is material analogy that is important in creative thinking. If the proportion format is useful at all it is as a controlled model of the comparison of two analogues, once selected, but we have claimed that even such a similarity is strained because in material analogy the comparison is guided by previously available information in a manner obscured by the proportion format. By studying components of analogical reasoning

outside of a context (except the context provided by the test), it becomes difficult to see how contextual and goal-oriented factors affect the comparison between analogues.

The use of analogies

In our account, reasoning by analogy draws upon information about previously encountered objects or situations to help us understand or deal with new ones. There is no requirement that the new situation fall under a concept identifying the analogue domain. For example, Freud drew fruitful analogies between a hydraulic system and motivated behavior, although any list of features of a hydraulic system will exclude the behavioral analogue. In this way, analogies are unlike templates, frames, or feature extraction models which require correspondances to be unambiguously pre-defined.

Our account has several potentially testable features. It holds that the criteria of causality guide the processes of analogue selection and comparison. Recognition of similar and dissimilar features is assumed to be simpler in some way than a feature analysis of each analogue separately. It assumes a task-relative retrieval system with something like a threshold of similarity rather than a "correct" or "incorrect" assessment. It suggests that component processes are not independent.

We recognize that since analogical reasoning does not yield unique conclusions or apodictic arguments it is not readily amenable to typical laboratory paradigms. Nevertheless we think the descriptions offered by philosophers such as Hesse and Harré are more likely to suggest fruitful approaches than a format ecologically adapted only to the intelligence test.

Footnotes

[1]Selection of the analogue is important in problem solving. Reed (1977; Reed, Ernst, and Banerji, 1974) reports experiments in which subjects were given alternative problems with the same logical structure, or formal problem space, e.g., formal analogies in Hesse's terms. Little transfer was found from one problem to another, suggesting a limitation of the use of analogical reasoning in problem solving. However, the problem Reed utilized (the cannibals-missionaries problem) is complex and difficult. Reed et. al. found, for example, that when they gave the same problem twice to the same subjects there was no reduction in the number of moves to solution (although less time was required). This suggests that there was inadequate internal representation for recall and consequently little reason to expect analogical transfer.

We have described the use of material analogy for problem identification (Klein and Weitzenfeld, 1976; 1978) and have presented an account of the place of acts of identification in the cognitive processes (Weitzenfeld 1977).

[2]Harré (1970) provides a taxonomy of models in science that is too elaborate to be summarized here, but that might serve heuristically in an analysis of the processes comparing subject and analogue.

[3]We leave as an open and interesting question whether any of these criteria are innate.

[4] Black (1962) calls this the interaction view of the explication of metaphor.

[5] Minsky (1975) and Schank and Abelson (1977) both attempt to include background knowledge in programs that analyze situations or events. Dreyfus (1979) gives a general account of how the need for representation of culture is gradually recognized by workers in AI.

[6] The history of philosophical studies of the concept of causality, however, generate doubts about the likelihood of finding an adequate account of causality to incorporate. Schank and Abelson (1977) have incorporated a model of causation in terms of acts and states into their text understanding system, but this is not the place to discuss its adequacy. There is a difference, moreover, between an account of causation adequate for some specific purpose and an account adequate for a general model of analogical reasoning.

[7] In recent years the hypothesis of analogical inferences has become more common (Baron, 1977; Johnson-Laird and Steedman, 1978; Brooks, 1978; Reber and Allen, 1978; Dreyfus & Dreyfus, 1979), but, with a couple of exceptions, this is a reference to reasoning from a previous experience and not an account of how the previous experience can be brought to bear on the present problem. None of the accounts of analogical reasoning approaches the completeness of Hesse's.

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